Efficacy of Cement-Stabilized GBS and GGBS Cushions in Improving the Performance of Expansive Soils

Sridevi Guda

Professor, B.V. Raju Institute of Technology, India.
E-Mail: gudasridevi@yahoo.co.in

ABSTRACT

Expansive soils undergo alternate swelling and shrinkage with changes in the moisture regime. As a result, structures founded in these soils undergo distress. Among the several techniques available to mitigate the problem, CNS layer technique is the one commonly adopted. Since this technique has certain limitations, an alternative method was tried with stabilized blast furnace slag for better results. Granulated blast furnace slag is one of the major by-products of steel plant industry. The disposal of it poses a big problem which, if not solved, causes environmental pollution. Detailed laboratory studies were carried out on this material to investigate its suitability as a construction material. Experiments were conducted to study the effect of the cement content as well as the cushion thickness on the heave of the expansive soil bed. Expansive soil for the study was collected from a depth of 1.5 m in order to see whether it contains no organic matter. The liquid limit is 73% and the plasticity index is 45%, which are very high and show that the soil has high potential for undergoing volume changes. A free swell index of 150% shows that the soil has a high degree of expansiveness. The expansive soil was compacted to its MDD at OMC and above it cement-stabilized blast furnace slag in the form of a cushion compacted to MDD at OMC was placed and the resulting heave was measured. Cement content, varying from 2% to 10%, with increments of 2% by weight, was added to GBS in dry condition and mixed thoroughly. Then, water corresponding to OMC was added and the layer placed above expansive soil bed and compacted to its MDD. Experiments were conducted for different thickness ratios of soil (ts) and cement-treated GBS (tc) given by tc/ts = 0.25, 0.5 and 0.75. Studies were also conducted using cement-stabilized ground granulated blast furnace slag cushion in the same way as mentioned above. It was found that granulated blast furnace slag cushion, stabilized with cement, was effective in arresting heave of expansive soils.

KEYWORDS: Expansive soil, Ground granulated blast furnace slag, Cushion, Heave, Swelling potential, CBR.

INTRODUCTION

In developing countries like India, provision of complete network of road system with limited finances by conventional methods and materials is a challenging task. To meet the growing needs of road traffic, often, stage-wise construction of low cost roads is preferred. Local materials, including local soils for the construction of the lower layers of the pavement-such as sub-base course and sub-grade soil-are always preferred. The local soils, such as clays, loess, marine clays and collapsible soils, exhibit inadequate strength and stability for supporting the wheel loads. Clays can

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be plastic and compressible tending to have low shear strengths and lose shear strength further upon wetting. Expansive soils are basically susceptible to detrimental volume changes with changes in moisture content. In some clays, these volumetric changes are very high, leading to failure of the structure. They tend to have low resilient modulus values. Cyclic expansion-contraction phenomena are related to seasonal fluctuations of the soil water content around areas of the building or pavement (Kassiff et al., 1969; Chen, 1975). It has been established that the stability and performance of pavement is reflected by soil sub-grade. Pavements constructed on expansive soils are bound to fail resulting in poor performance and increased maintenance cost. The damage caused by expansive soils amounts to billions of dollars all over the world. Recent research findings enabled engineers to put forth several remedial techniques to mitigate these damages (Nelson and Miller, 1992). Several techniques, such as belled piers, drilled piers, friction piles and moisture barriers, were developed to minimize the problems posed by expansive soils. Stabilizing expansive soils with admixtures, like lime, cement, chemicals,… etc., were tried and found to be effective, but uniform blending of large quantities of soils with admixtures is extremely difficult. Among the several methods for arresting the swelling of expansive soil, providing a cushion atop is commonly adopted. Various cushion materials, such as sand, sand and boulders, murrum,… etc., are used in practice and are found to perform adequately when the expansive soil shows low to moderate swelling. Based on experimental studies, Katti (1978) proposed the CNS cushion technique and suggested the thickness of cushion, specifications of the materials and placement conditions to get the best performance of the cushion. But, later studies by Subba Rao (1999) showed that the CNS layer becomes ineffective after the first swell-shrink cycle. Stabilized fly ash cushion technique developed by Rao et al. (2007) has yielded very promising results in arresting heave. It is observed that stabilizing agents, like lime or cement, react with reactive silica present in the fly ash to produce cementitious bonds that help in arresting heave. In developing countries, industrial wastes are no longer considered as wastes and studies have been carried out to explore the possibility of using them in geotechnical applications. Mathur et al. (1997) reported the suitability of slag obtained from steel industry as an aggregate in pavements.

Granulated blast furnace slag is a by-product obtained in the manufacture of pig iron in the blast furnace and is formed by the combination of iron ore with lime stone flux. The molten slag is cooled and solidified by rapid water quenching to glassy state, which results in the formation of sand size fragments. The gradation and physical structure of the blast furnace slag depend on the chemical composition of the slag, its temperature at the time of water quenching and method of production (Lee, 1974). Blast furnace slag has a glassy, disordered, crystalline structure which can be seen by microscopic examination which is responsible for producing a cementing effect. GGBS is cementitious on its own. It is a hydraulic material and therefore requires no additives for hydration and hardening to take place other than water if hydrated at an elevated temperature and for a long time (Song et al., 2000). The main constituents of the slag are lime, alumina, silica and magnesia. Higgins (1998) observed that GGBS on its own has only mild cementitious properties and in conventional concrete it is used in combination with Portland cement whose alkalinity provides the catalyst to activate the cementitious properties of the GGBS. He also reported that lime (calcium hydroxide) could provide the necessary alkali for activation. However, BS 6699, British Standard specification for GGBS for use with Portland cement (1986), specifies a requirement that (CaO+ MgO+ $A1_2O_3$)/ SiO_2 should be greater than 1. In addition, as the CaO/ SiO_2 ratio increases, the rate of reactivity of the GGBS also increases up to a limiting point at which increasing the CaO content makes granulation to glass difficult. For optimum hydraulicity, the CaO/ SiO_2 ratio would need to be around 1.5. In most applications, activation of GGBS is required which can be achieved by blending calcium hydroxide, calcium sulphate, ordinary Portland cement, sodium hydroxide, sodium carbonate and sodium sulphate (Gjorv, 1989). Calcium sulphate is a successful activator apart from performing an important role as a reactant (Taylor, 1986; Daimon, 1980). A reactant participates significantly in the reaction process, while an activator creates an appropriate environment for the reaction process without necessarily participating in the reaction.

In India, about 15 million tons of slag are produced annually from steel plants (Singh et al., 2008). Environmentally safe disposal of large quantities of slag is not only expensive, but also poses problems in the form of land use and health hazards. With the rise in carbon emissions resulting in global warming and climate change, innovative methods are vital. Studies are conducted using GGBS with small amounts of cement (Cockka, 2009). The production of GGBS involves a carbon dioxide emission of only 30% compared to cement production. Numerous additives, such as cement kiln dust, rice husk ash, marble powder, fly ash and GGBS, have been tried over the past decades and their usefulness and efficiency in terms of improvement in geotechnical properties are well established by several researchers (Kolawole Juwunlo Osinubi, 2006; Indraratna, 2005; Tasong et al., 1999; Wilkinson et al., 2010). In some sulphate bearing clays, excessive swelling was observed when the soil was stabilized with lime. Following this, research was carried out with ground granulated blast furnace slag (GGBS). It was found that GGBS can reduce the expansive tendencies of lime-stabilized sulfate bearing clays (Wild et al., 1998). Blending cement with GGBS produces well-established sulphate-resisting properties in concretes. Studies were conducted with GGBS-stabilized expansive soil with and without lime as a cushioning material on the expansive soil sub-grade and considerable reduction was found in the swelling of the expansive sub-grade soil. Moreover, disposal of these materials is not only cost intensive, but also requires valuable land. As such, efforts are made in this direction exploring the possibility of using these materials alone or in combination with other additives. However, the performance and efficiency of these additives are influenced by several parameters, like chemical and mineralogical composition of the soil, as well as geotechnical properties of the additives.

So, in the present work, the industrial waste blast furnace slag that contains substantial amounts of silica and alumina, is used with cement as stabilizing agent to form a cushion on the top of the expansive clay bed. Blast furnace slag was used in two forms: the nodule form and the ground form.

Hydration Mechanism of Portland Cement-GGBS Mixture

Upon addition of water to a GGBS cement mixture, hydration takes place and water begins to combine with Portland cement to form calcium silicate hydrate. The other reaction products of Portland cement are calcium hydroxide and later sodium and potassium hydroxides. These alkalis activate the GGBS which reacts with water to produce hydrates similar to those produced by Portland cement hydration. The GGBS, due to its high alumina and silica content, produces somewhat more complex hydrates than ordinary Portland cement (OPC). Precipitates of calcium silicate hydrates and calcium aluminate hydrates resulting from the hydration reaction cause the excess silicates and aluminates from the GGBS hydration to combine with calcium hydroxide in a pozzolanic reaction. The above reactions take place in sequential order. The first stage starts immediately and stage four takes much longer time to finish. Therefore, the strength development of Portland cement/ GGBS is slower than Portland cement alone (Wild et al., 1998).

OBJECTIVES OF THE STUDY

a. To study the swelling behaviour of expansive soil when cement-stabilized granulated blast furnace slag cushion and cement-stabilized ground granulated blast furnace slag cushion with varying cement contents were placed over it.
b. To compare the performances of granulated blast

furnace slag (GBS) and ground granulated blast furnace slag (GGBS) cushions.

c. To study the effect of cushion thickness on the swelling behaviour of expansive soil.
d. To evaluate the soaked CBR of cement-stabilized GBS-soil system and cement-stabilized GGBS-soil system.

MATERIALS

Soil: The soil used in the study was collected from Chuttugunta, Guntur Dist., in Andhra Pradesh, India. While collecting the soil, it was ensured that the material did not contain any organic matter. The properties of the soil are presented in Table 1. The liquid limit is 73% and the plasticity index is 45%, which are very high and show that the soil has high potential for undergoing volume changes. A free swell index of 150% shows that the soil has a high degree of expansiveness.

Granulated Blast Furnace Slag (GBS) and Ground Granulated Blast Furnace Slag (GGBS): The material was procured from the Visakhapatnam Steel Plant, Visakhapatnam. The geotechnical and the chemical properties of granulated blast furnace slag are given in Table 2 and Table 3. The geotechnical properties of GGBS are given in Table 4.

Cement: Cement used in the study was 53-grade ordinary Portland cement.

Table 1. Geotechnical properties of expansive soil

Grain-Size Distribution	
Sand (%)	27.2
Silt and Clay (%)	72.8
Liquid Limit (%)	73
Plastic Limit (%)	28
Plasticity Index (%)	45
Shrinkage Limit (%)	14
IS Classification	CH
Specific Gravity	2.68
OMC (%)	25
Maximum Dry Density (Mg/cum)	1.56
Free Swell Index (%)	150
CBR (%) (Soaked)	0.99

Table 2. Geotechnical properties of granulated blast furnace slag

Specific gravity	**2.2**
Grain-size distribution: Fine sand size (0.425 to 0.075 mm) (%) Silt and clay sizes (%)	 98.5 1.5
Maximum dry density (Mg/m^3)	1.50
Optimum moisture content (%)	24.4
c, Cohesion (kPa) (undrained)	20
ϕ, Angle of internal friction (degrees)	15
Soaked CBR (%)	4.3

Table 3. Chemical composition of granulated blast furnace slag

Name of chemical	Symbol	% by weight
Silica	SiO_2	27 -38
Alumina	Al_2O_3	7 – 15
Ferric Oxide	Fe_2O_3	0.2 – 1.6
Manganese Oxide	MnO	0.15 – 0.76
Calcium Oxide	CaO	34 – 43
Sulphur Trioxide	SO_3	up to 0.07
Potassium Oxide	K_2O	0.08 - 1.83
Sodium Oxide	Na_2O	0.20 - 0.48
Loss on Ignition		0.20 - 0.85

* Data Source: National Slag Association.

Table 4. Geotechnical properties of ground granulated blast furnace slag

Specific gravity	**2.85**
Grain-size distribution: Fine sand size (0.425 to 0.075 mm)(%) Silt and clay sizes (%)	 73 27
Maximum dry density (Mg/m^3)	1.80
Optimum moisture content (%)	15.0
Plasticity Index (%)	NP
Free Swell Index (%)	0
Soaked CBR (%)	6.2

HEAVE STUDIES

A schematic diagram of the experimental set up for heave studies is shown in Figure (1). The experimental study was carried out in galvanized iron (G.I.) cylindrical test moulds, 280 mm in diameter and 600 mm in height. A 10 mm thick sand layer, compacted to its maximum dry density and OMC, was laid at the bottom of the mould. A cylindrical casing made of G.I., 190 mm in diameter and 300 mm in height, was placed centrally in the test tank. The gap between the casing and the test mould was filled with coarse sand compacted to its maximum dry density and OMC in order to serve as draining face while saturating the sample. The expansive soil was compacted to its MDD and OMC in 4 layers, each 50 mm thick. A hollow PVC pipe was placed on the top of the soil layer before the GBS layer was compacted. Cement content, varying from 2% to 10%, with increments of 2% by weight, was added to GBS in dry condition and mixed thoroughly. Then, water corresponding to OMC was added and the layer placed above the expansive soil bed and compacted to its maximum dry density. After the cement-stabilized GBS layer was compacted, heave stake was placed through PVC pipe on the top of the clay bed. A dial gauge was mounted on the top of the heave stake. After noting the initial reading on the dial gauge, water was admitted into the test tank in order to saturate the sample and the heave of the soil recorded. The process was continued till there was no change in the dial gauge reading. After the soil specimen has completely swollen, the moisture content was found to ensure whether the sample was fully saturated or not. Experiments were conducted for different thickness ratios of soil (t_s) and cement-treated GBS (t_c) given by t_c/t_s = 0.25, 0.5 and 0.75. Studies were also conducted using cement-stabilized ground granulated blast furnace slag cushion in the same way as explained above.

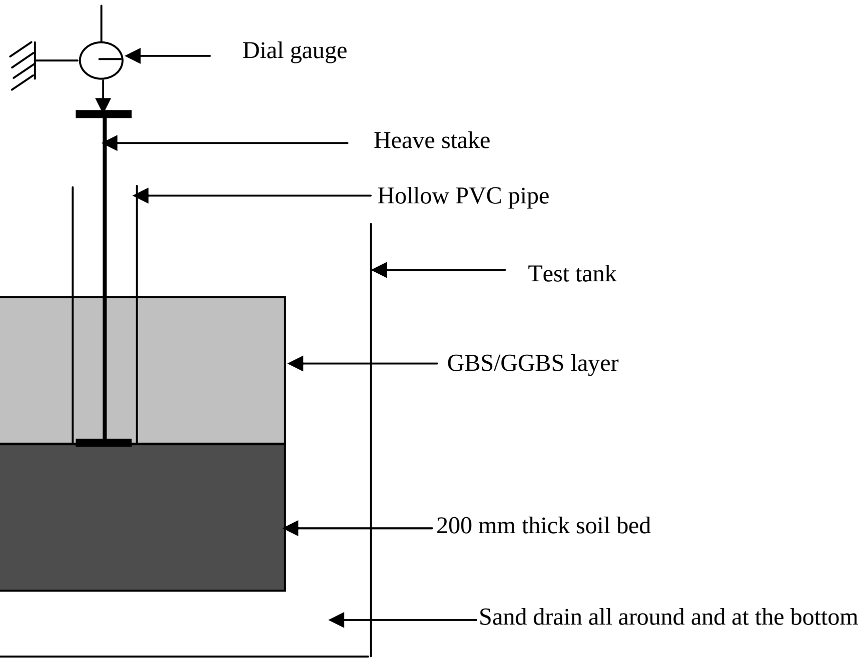

Figure (1): Experimental set-up for swelling studies

Variables Studied

Cement content added to the GBS/GGBS cushion (%)	2.0, 4.0, 6.0, 8.0 and 10.0
Ratio of thickness of cushion to the expansive soil bed t_c/t_s	0.25, 0.5 and 0.75

RESULTS AND DISCUSSION

Effect of Cement Content

The effect of cement content used for stabilizing blast furnace slag is shown in Figure (2). Figure (2) shows the variation of swelling potential with the cement content for different ratios of the thickness of the stabilized blast furnace slag cushion (t_c) to the soil bed thickness (t_s). The ratio of heave of expansive soil bed to its initial thickness, expressed as a percentage, is called the swelling potential of the soil. From Figure (2), it can be seen that the swell potential the decreases with the increase in cement content. However, for low percentages of cement content, the reduction in swell potential is very small, but beyond 4% cement content, there is a substantial decrease in swell potential. The silicates present in granulated blast furnace slag react with calcium ions present in the cement in the presence of moisture to form water insoluble calcium - aluminosilicates which are in the form of a gel. The pozollanic reactivity depends on parameters like reactive silica, free lime and their specific surface. At low cement contents, the free lime available in cement is not sufficient for the pozzolanic reaction; hence there is only a small reduction in swell potential. As the cement content is increased, greater quantity is available to penetrate into the pores of GBS for the pozzolanic reaction with reactive silica present in the slag, which results in considerable reduction of the swell potential. The reduction in swell potential beyond 8% cement content is not appreciable, because the free lime present in the cement reacts with the available reactive silica present in the slag and further addition of cement will be of no use, because there is no reactive silica present in the slag. However, free lime content can be supplemented by an external source, whereas the reactive silica cannot be supplemented.

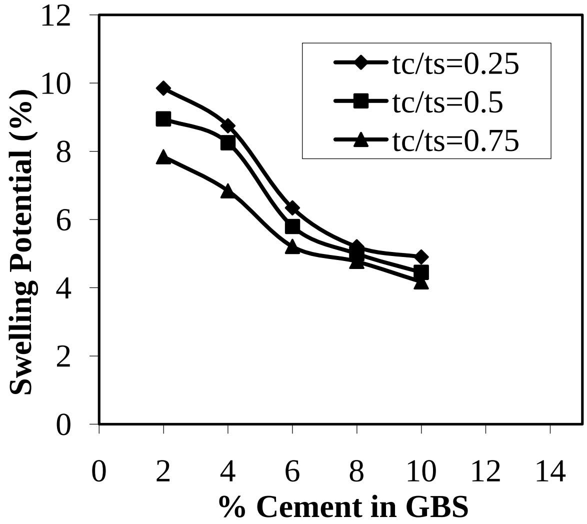

Figure (2): Variation of swelling potential with % of cement in GBS

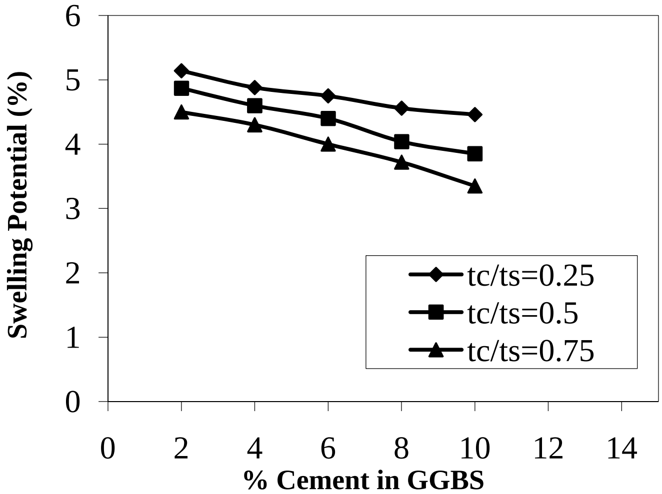

Figure (3): Variation of swelling potential with % of cement in GGBS

Effect of Cushion Thickness

Effect of thickness of cement-stabilized blast furnace slag layer on swell potential can also be seen in Figure (2). It can be seen that swelling potential decreases with the increase in the thickness of the GBS layer. The swell potential of clayey bed without any cushion was found to be 19% and there is a marked decrease in swell potential when stabilized blast furnace slag cushion was placed over the clay bed. For a cement content of 10%, the swell potential of expansive clay was reduced to 3.57% because of the development of cementitous bonds. The swell potential may further come down if the super structure is built because of increase in physical overburden on the expansive clay bed. Hence, stabilizing expansive soils using blast furnace slag cushion could be a better alternative for reducing heave in the areas nearby steel plants, as this proves to be economical apart from solving the disposal problem.

Effect of Cement Content and Cushion Thickness of Ground Granulated Blast Furnace Slag Cushion

Figure 3 shows the variation of swelling potential with cement content for different ratios of cement-stabilized ground granulated blast furnace slag cushion to the thickness of expansive clay bed. It can be seen that swelling potential decreases with the increase in cement content for all the different cushions provided. A considerable reduction in swell potential is observed even for a small amount of cement content. For t_c/t_s = 0.25 and a cement content of 2%, the reduction in swell potential of expansive clay was observed to be 73% with respect to uncushioned clay bed. Since ground granulated blast furnace slag is in the form of fine powder, more surface area is available for the reaction between lime present in cement and silica and alumina present in GGBS. As a result, cementitious bonds develop more freely, which are responsible for arresting the heave of the expansive clay bed. However, upon increasing the cement content, there is negligible reduction in the swell potential. From the figure, it can also be seen that the swelling potential decreases considerably when the thickness of the cement-stabilized GGBS cushion is increased. For t_c/t_s = 0.75 and a cement content of 10%, the reduction in swell potential of expansive clay was observed to be 82% with respect to uncushioned clay bed. Ground granulated blast furnace slag cushion is more efficacious in reducing the heave of expansive soils. The relative performance of different cushions in the reduction of heave is presented in Table 5.

Table 5. Relative performance of different cushions

Type of cushion	Swelling potential (%)	% Reduction with respect to uncushioned soil bed
No cushion	19	
Cement-stabilized GBS cushion	4.17	78
Cement-stabilized GGBS cushion	3.35	82

CBR Studies

California Bearing Ratio (CBR) tests were performed on the soil samples as per the Bureau of Indian Standard specifications (IS:2720-part: 16, 1979), in soaked condition. In the experimental study, CBR samples were prepared for different thickness ratios of the stabilized GBS/GGBS cushion (t_c) and the expansive soil bed (t_s). Both the soil bed and lime-treated GBS/GGBS were compacted to their respective MDD and OMC values in the same manner as in the case of heave studies. Lime content of the cushioning material was varied from 2% to 10%, with increments of 2%. After compaction, a surcharge weight of 5 kg, sufficient to produce intensity equal to the weight of the base material and the pavement, was placed during soaking and penetration. A metal penetration plunger of a diameter of 50 mm was used to penetrate into the samples at a rate of 1.25 mm/min. Three CBR tests were conducted on each specimen and the average of the three was reported. Both heave and CBR studies were conducted for different thickness ratios of the soil (t_s) and the lime-treated cushion (t_c), given by t_c/t_s=0.25,0.5 and 0.75 corresponding to the different lime contents used in the cushion.

Effect of Cement- Stabilized GBS Cushion and Cement-Stabilized GGBS Cushion on Soaked CBR of Expansive Soils

The soaked CBR of blast furnace slag in nodule form (GBS) was found to be 4.3% and that in ground form was 6.2%. With the addition of an activator, a considerable increase in soaked CBR was observed. Fig.4 shows the variation of the soaked CBR with the different thickness ratios of cement-stabilized GBS cushion and the expansive clay bed. From Fig.4, it is evident that the soaked CBR increases with an increase in the thickness of the cushion. It can also be seen that as the cement content increases, an increase in the soaked CBR occurs, which is due to the pozzolanic reaction between the lime present in the cement and the silica present in the GBS. GBS has both cementitious and pozzolanic properties. Fig.5 shows the variation of the soaked CBR with the different thickness ratios of cement – stabilized GGBS cushion and the expansive clay bed. When mixed with water, GGBS develops its hydraulic reaction (Feng, 2004). However, at room temperature, GGBS is normally not a hydraulic material. Activators are required to initiate hydration. If GGBS is placed in water alone, it dissolves to a small extent, but a protective film deficient in Ca^{2+} is quickly formed, which inhibits further reaction. During initial hydration, the reaction of GGBS produces aluminosilicate and coats on the surface of GGBS grains within a few minutes of exposure to water and these layers are impermeable to water, inhibiting further hydration, the reactions (Daimon, 1980; Caijun et al., 1993). Richardson et al. (1994) found only a small amount of C-S-H which formed after 150 days of moist curing. Therefore, GGBS used on its own shows little hydration. Reaction continues if the pH is kept sufficiently high. The pore solution of a lime, which is essentially an alkali hydroxide, is a suitable medium. The presence of solid $Ca(OH)_2$ ensures that the supply of OH^- is maintained (Taylor, 1997). The final products of the GGBS reaction are similar to the products of cement hydration, but the rate and intensity of reaction differ. Slag also exhibits pozzolanic reactivity in the presence of calcium hydroxide (Mindess, 2003). The pozzolanic reaction takes place in which calcium hydroxide is consumed to form secondary calcium silicate hydrates. The primary factors of slag which influence hydration are: chemical composition of the GGBS, alkali concentration of the reacting system, glass content of the GGBS, fineness of the GGBS and temperature during the early phases of the hydration process. Upon soaking, the lime present in the cement reacts with the reactive silica present in the GGBS, which is responsible for the formation of cementitious bonds. Further, internal friction between the particles of GBS either in granular form or ground form also contributes to the increase in the value of CBR. The hydration products of GGBS are found to be more crystalline than the hydration products of Portland cement and so add density to the cement paste (Taylor, 1990; Smolczyk, 1980). Erdal Cokca (2008) studied the effect of ground granulated blast furnace slag (GGBS) and GBS-cement with a view to decrease the construction cost. It was found that there was a decrement of 62% in the swelling potential with GGBS-treated soil compared to virgin soil.

Sharma and Shivapullaiah (2012) studied the compaction behavior and effect of unconfined strength of soil stabilized with fly ash and GGBS. They found that the addition of GGBS with and without fly ash and lime has significant influence on the geotechnical characteristics of the soil.

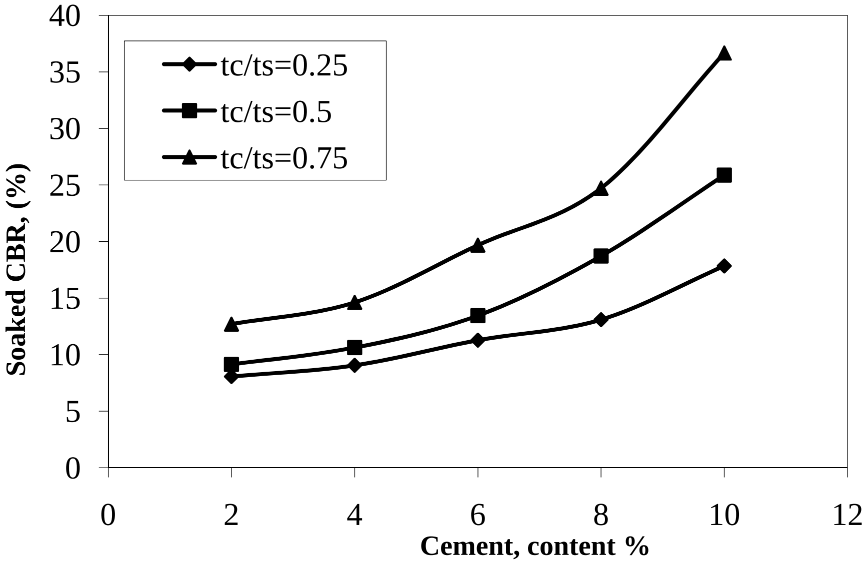

Figure (4): Variation of soaked CBR for different cement contents in GBS

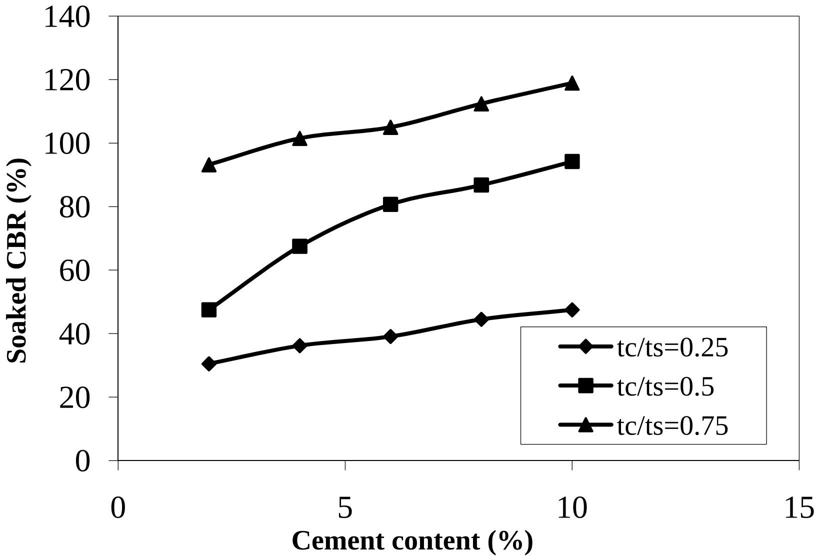

Figure (5): Variation of soaked CBR for different cement contents in GGBS

Hence, it can be inferred that cement-stabilized GBS as well as GGBS cushion are effective in improving the soaked CBR of the cushion-expansive soil system.

The changes of microstructural development of GGBS due to the addition of lime and cement play a significant role in altering the geotechnical properties and the mechanical behavior of the stabilized mixes. The microstructures of the three materials *viz*. GGBS and cement-stabilized GGBS are presented in Fig.6, Fig.7 and Fig. 8. Fig.6 is a scanning electron micrograph showing the characteristic morphology of the GGBS. This material consists of particles of different sizes and shapes and there is no evidence of hydration of the GGBS. GGBS is a latent hydraulic material and alkali should be added to initiate the pozzolanic reaction. Fig. 7 and Fig. 8 show the SEM of GGBS stabilized with 2% cement and 4% cement, respectively. As could be seen from the figures, the matrix becomes more impervious upon increasing the cement content. Cement- stabilized GGBS appears like a continuous phase as separation of particles is not observed.

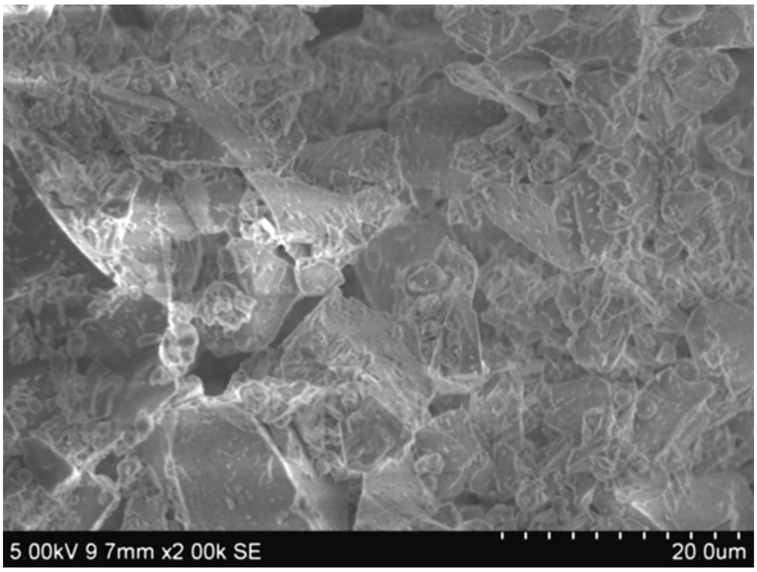

Figure (6): Scanning electron micrograph of GGBS

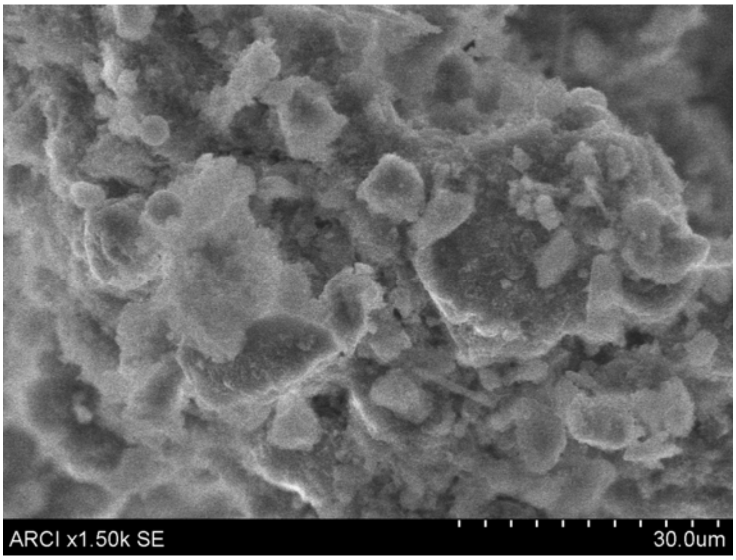

Figure (7): Scanning electron micrograph of GGBS stabilized with 2% cement

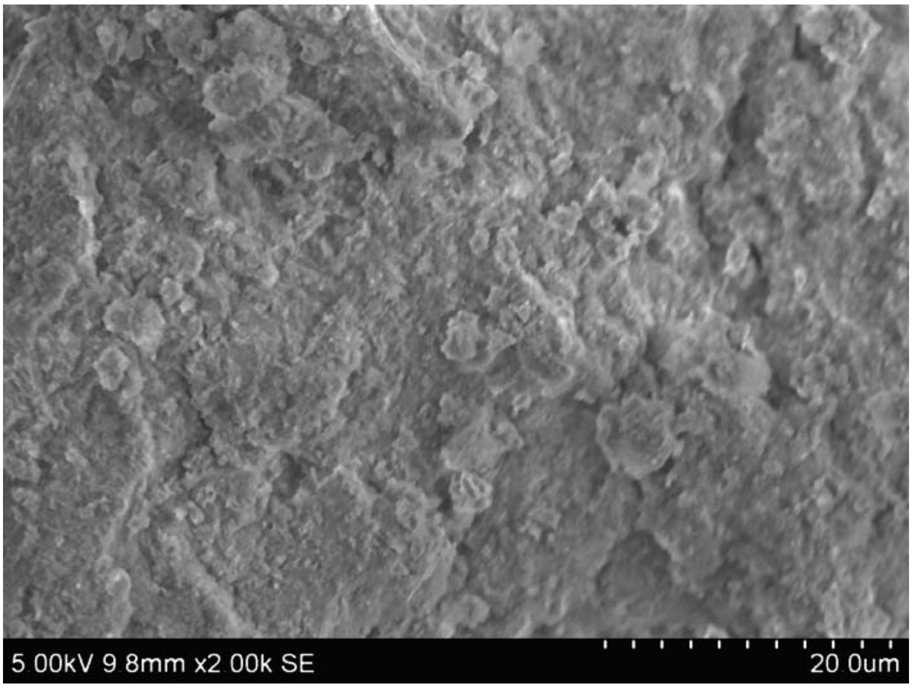

Figure (8): Scanning electron micrograph of GGBS stabilized with 4% cement

CONCLUSIONS

Blast furnace slag and ground granulated blast furnace slag cushions, stabilized with cement, are effective in minimizing the swell of expansive soils. For GGBS cushion, there is a significant reduction of heave at low cement contents.

However, in the case of GBS cushion, as the cement content is increased, the swell potential decreases steeply. 6%-8% cement content has been found to be optimum. With the increase in the thickness of the cushion, there is a corresponding decrease in the swell potential.

Soaked CBR was found to increase in both cement-stabilized GBS-clay system as well as cement-stabilized GGBS-clay system. As the cement content is increased, the soaked CBR increased continuously and as the thickness of the cushion material is increased, there is an increase in the soaked CBR. At room temperature, activators are required to initiate hydration of GGBS. In the absence of activators, when GGBS is placed in water alone, it dissolves to a certain extent, but a protective film deficient in Ca^{2+} forms which inhibits further reaction. GGBS with 2% of cement as activator can be used as cushioning material to minimize the heave of expansive soil and this cement-stabilized expansive soil cushion system has increased soaked CBR which improves the performance of pavements.

Abbreviations

GBS: Granulated Blast Furnace Slag.
GGBS: Ground Granulated Blast Furnace Slag.
CNS: Cohesive Non-Swelling.
MDD: Maximum Dry Density.
OMC: Optimum Moisture Content.
CBR: California Bearing Ratio.

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